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A Search for Optical Counterparts to Supersoft X-Ray Sources in the ROSAT Pointed Database

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Abstract: We present a progress report of our program to identify optical counterparts of supersoft X-ray sources detected serendipitously during pointed ROSAT PSPC observations.

We generate a parent sample of ~4100 supersoft sources by starting with the WGA (Whi94) and ROSAT SRC (Zim94) catalogs, extracting X-ray detections on the basis of softness (ROSAT HR1 ≤ -0.5), condensing multiple detections, and combining sources seen in both catalogs. This unwieldy sample is divided into four (occasionally overlapping) subclasses: (1) a flux limited sample (WGA only) encompassing ~120 square degrees of sky, (2) an all-sky "extremely soft" sample (HR1 ≤ -0.8), (3) an optically bright all-sky sample with candidates $V \lesssim 14.5$, and (4) an all-sky sample near the nuclear burning white dwarf (NBWD) track in the HR1-HR2 plane, as defined with Monte Carlo simulations.

This program has been underway for about one year and has included seven observing runs at the MDM observatory at Kitt Peak, Arizona. In addition, numerous sources have been identified via catalog and literature searches. More observing runs are currently scheduled. Although no new NBWDs have been discovered yet, we have found many new supersoft AGN and emission stars, and a few new white dwarfs and CVs. By the conclusion of our program we will be able to set constraints on models concerning the population of NBWD, to understand the proportions of objects that make up the class of "supersoft X-ray sources," to investigate models for the supersoft nature of AGN, and (hopefully) to discover some new NBWD systems.

1 Introduction

One of the interesting contributions of the ROSAT satellite is the discovery of celestial objects possessing such soft X-ray spectra that over 75% of the counts are detected between 0.1 and 0.4 keV. These "supersoft X-ray sources" (SXS) themselves do not form a uniform group, but rather a collection of astrophysical systems including hot white dwarfs, stars with active coronae, cataclysmic variables (CVs), white dwarfs undergoing surface nuclear burning of accreted matter (NBWD), active galactic nuclei (AGN), and galaxies with warm halos.

A large number of SXS were discovered in the ROSAT All-Sky Survey (RASS) conducted during the first 6 months of the mission. The average exposure time to any portion of the sky was ~500 seconds. Between that time and November, 1994, there years of pointed guest observations were accumulated with ROSAT. Two groups, one in Germany and one at NASA — Goddard Space Flight Center, independently searched these data for serendipitous sources,with each group creating a catalog of their results. Each catalog contains about 50,000 detections, covers about a quarter of the sky, and yields a typical exposure time on any one source of about 11,000 seconds. Typical uncertainties in source location are 30″ (90% confidence error radius). This database provides a new SXS sample that is complementary to the RASS and more comprehensive, in the overlapping energy bands, than the EUVE or ROSAT WFC surveys (400-500 sources each).

We have undertaken a large program to find optical counterparts to SXS detected in these new databases. Upon completing the optical search, follow-up studies, and additional supporting projects, we will be able to: (1) determine in a statistically meaningful manner the composition of the general class "supersoft X-ray source," (2) test theoretical predictions regarding mass transfer in NBWD systems by modeling the orbital structure, (3) test theoretical predictions regarding populations of NBWD in the Galaxy, (4) discover new NBWD systems to a flux ten times fainter than that of the only such unobscured galactic system, (5) determine whether preliminary conclusions drawn during similar studies of the RASS sample still hold at deeper flux limits, and (6) provide a sound model (incorporating X-ray data) as to the nature of supersoft AGN.

This paper is a report on our ongoing program. In Section 2 we discuss the selection of targets for optical observation, in Section 3 we provide the current status of the program, and in Section 4 we present preliminary results of our work.

2 Program Definition

The Goddard (WGA) and German (SRC) ROSAT catalogs report not only the position of each source, but also spectral information. We define the following spectral bands:

$$\begin{aligned} \mathrm{A} &= 11 - 39 \text{ ADU} \approx 0.1 - 0.4 \text{ keV} \\ \mathrm{B} &= 40 - 85 \text{ ADU} \approx 0.4 - 0.9 \text{ keV} \\ \mathrm{C} &= 86 - 200 \text{ ADU} \approx 0.9 - 2.0 \text{ keV}, \end{aligned}$$

and form two hardness ratios

$$\mathrm{HR1} = \frac{(\mathrm{C}+\mathrm{B}-\mathrm{A})}{(\mathrm{C}+\mathrm{B}+\mathrm{A})} \qquad \mathrm{HR2} = \frac{(\mathrm{C}-\mathrm{B})}{(\mathrm{C}+\mathrm{B})}.$$

We select all detections with HR1 ≤ -0.5 from both catalogs. After this selection only ~5% of the original catalog remains of interest. This list is further condensed by looking for multiple detections of the same object. In the end, 4101 individual SXS remain to be identified; we define this as the "parent sample."

A literature search was conducted for each object in the parent sample, both through the SIMBAD database and catalogs compiled at MIT. In the end, about 500 sources could be identified through such literature searches[1], leaving over 3500 sources to be identified with optical counterparts. It is not feasible to carry out so many observations in a reasonable amount of time. To effectively achieve the goals of this program, we have defined four (occasionally overlapping) subsamples.

2.1 Flux Limited Sample

In order to determine what proportion of the SXS are of various classes (CVs, AGN, etc.) in a statistically meaningful way, we have defined a flux limited sample of SXS. In this sample we restrict ourselves to the WGA catalog because of the careful consideration of point spread function effects for sources far off-axis (Hab94). Care has been taken to select objects with similar exposure times and interstellar absorption characteristics such that the ROSAT PSPC count rate can be used as a measure of flux. The resultant log(dN/dS)-log(S) plot is shown in Figure 1. We have chosen a (conservative) lower flux limit of 0.014 cnts/s; Fig. 1 indicates that the X-ray data are complete to even lower values of the flux. This sample covers about 120 square degrees of sky and contains 177 sources. We will consider this sample adequately studied when 90% of the SXS have been identified with optical counterparts.

In addition to determining the constituency of the SXS, the flux limited sample will serve as a basis for studying SXS AGN. Table 2 (presented in Section 4) indicates that we will identify a large number SXS AGN from which we will be able to determine a luminosity function. We will look for signs of evolution in this distribution and compare it to other luminosity functions of general X-ray selected AGN.

2.2 Extremely Soft Sample

To be classified as "supersoft," a source requires an HR1 value of ≤ -0.5 (75% of the counts in band A); however, there are a number of reasons to consider the very softest sources with HR1 ≤ -0.8 (90% of the counts in band A) distributed over the entire sky. To begin, NBWD systems are very soft, and it is a stated goal of this program to find more of these systems. In fact many of the known NBWD systems have been found in this range. Next the 0.1 - 0.4 keV region is being explored with great sensitivity for the first time with the ROSAT satellite. Therefore the identification of sources in this band is potentially rich in new phenomena. This sample includes 355 SXS; our goal is to determine optical counterparts for 90% of them.

[1] The literature search is an on-going process. We are continually seeking and searching additional catalogs.

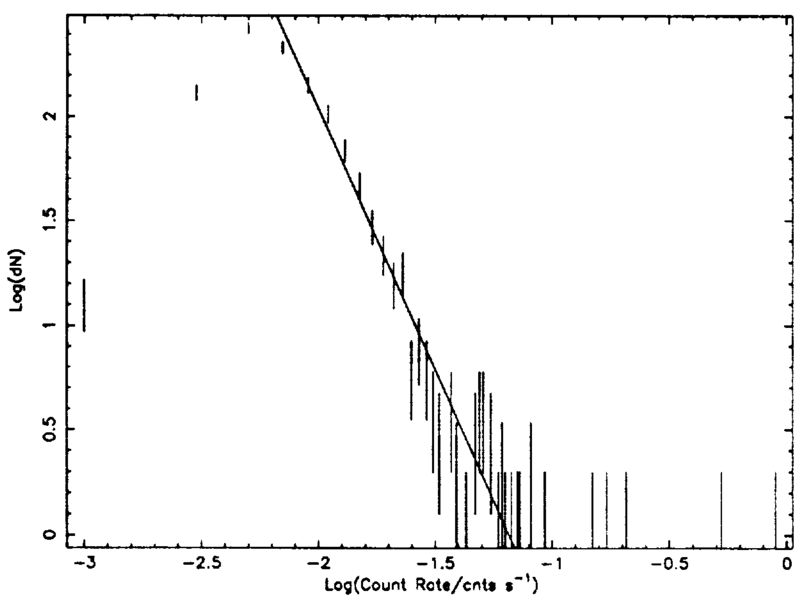

Fig. 1. Log(dN/dS)-Log(S) plot for the flux limited sample. A -5/2 power law is shown. We take a conservative completeness limit of 0.014 counts/s.

2.3 Optically Bright Sample

Due to the very soft X-ray spectrum of a NBWD, any such object in the Milky Way detected by ROSAT is probably quite local because interstellar attenuation of soft X-rays would make more distant sources undetectable. At the same time, NBWD can be very luminous ($\sim 10^{38}$ erg/s). The combination of these properties might well result in an optically bright counterpart. For example RXJ0019+2156, the only unobscured galactic NBWD known, has $m_V \sim 12.8$ (Beu95a). The opportunities that would arise from the discovery and study of a new NBWD system have prompted us to define a sample of all stars brighter than $V \sim 14.5$ within 1.3 error radii of the X-ray position (at 1.3 error radii the optical counterpart should be enclosed with a probability of 96%). A comparison of the parent sample to the Space Telescope Guide Star Catalog (ST-GSC) yields 694 stars meeting these criteria, distributed among 640 SXS. Although the ST-GSC is generally complete to 14.5 magnitude, this limit can can be significantly worse for dense fields. In these cases we attempt to include stars neglected in the ST-GSC via direct inspection of the finding charts produced with the Digital Sky Survey. This portion of the program will be considered complete when 90% of the stars have been observed and determined to be (or not to be) of the NBWD class.

2.4 Monte Carlo Sample

We also take another approach to finding galactic NBWDs among the 80,000 detections in the WGA and SRC catalogs, by generating a simulated catalog with only a population of NBWD distributed throughout the Milky Way. Using a simple "disk + bulge" model for interstellar gas, the column density to any point in the simulated galaxy can be analytically determined. The NBWD are placed in a disk population with a space density that decays exponentially with height above the midplane. The scale heights for the NBWDs and gas are taken to have the ratio $z_{NBWD}/z_{gas} = 0.5$ (following DiS94), and their spectra (taken to be simple blackbodies) are selected from a luminosity-temperature distribution determined by Rappaport et al. (Rap94). The probability of choosing any given (L,T) was weighted by the expected lifetime of that system.

The intrinsic spectrum from each NBWD is modified by interstellar absorption, then "observed" by folding the incident spectrum through the ROSAT PSPC response matrix.

In order to be consistent with the actual catalogs, after including the effects of background and Poisson noise, we demand a signal-to-noise ratio ≥ 5.0 to be secure in a "detection." Only the count rate and the number of counts in channels A, B, and C are accumulated. The goal is to find relations among these spectral parameters which constrain the parameter space that is likely to contain Galactic NBWD.

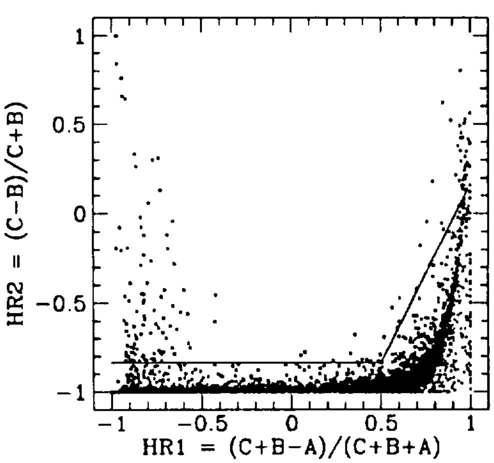

Fig. 2. Distribution of simulated galactic NBWD in the HR1-HR2 plane. 5000 "detections" from 46,464 seeded systems are plotted.

Figure 2 shows a very clear relation between HR1 and HR2 which agrees very well with known nuclear burning white dwarf systems. Based on this result, we are currently defining a fourth sample (the area below the line in Fig. 2) to optimize our search for NBWD[2].

[2] Other researchers have independently drawn similar conclusions utilizing other methods (e.g., C. Motch (Mot94) and P. Kahabka (Kah96)).

3 Current Status

At the time this article was written we were about half way through the observing program. In about 50 nights of observing time we have taken 939 spectra, all but 5 on the Michigan - Dartmouth - MIT (MDM) 1.3 meter observatory atop Kitt Peak, Arizona. An additional 20 nights are scheduled in the first half of 1996.

Table 1. Current status of the sub-samples

Sample	Total Sources	To Be Observed	IDs (New)
Flux Limited	177	148	30 (10)
Extremely Soft	355	203	151 (5)
Optically Bright	694	134	147 (13)
Other	3035	2746	289 (18)

Table 1 shows our progress on each subsample. The optically bright sample is virtually complete. The flux limited sample needs the most work; however, this sample was least conducive to study with the MDM 1.3m. Upcoming time on the MDM 2.4m should be highly productive in this regard. Note we are taking a very strict definition of "new identification" at this time. Most notably we have not finished analyzing the ordinary stars, over 200 of which are probably optical identifications. This uncertainty is also reflected in Table 2 below.

4 Preliminary Results

A brief summary of our results to date is shown below in Table 2; general trends can be extracted from this information. The trends found in the RASS sample of SXS toward large numbers of SXS AGN (Gre95) and a predominance of SXS CVs being of the AM Her type (Beu95b) continue to hold in the pointed survey.

Each sub-sample tends to have its own "signature class". The flux limited sample is dominated by SXS AGN (20 of 30 identified systems), The extremely soft sample is predominately white dwarfs and AM Her CVs, and the optically bright sample consists mainly of emission stars and white dwarfs.

New identifications are being made at a steady pace, mainly among AGN and emission stars. The fact that we have not made more firm identifications stems from a few things. Most of our observations have taken place on the MDM 1.3m during bright time. Next, the CCD used in most of the observations does not have sufficient blue response to examine the CaII H and K lines ($\lambda\lambda 3933, 3969$) which are excellent indicators of active coronae. As a result we have focused on the optically bright sample (see Table 1) which could be most easily carried out under these conditions. The Spring 1996 runs have been optimized to explore the other samples where actual identifications are the goal.

Table 2. Current SXS identifications by class and subsample

Class	Total (New)	Flux	Soft	Optical	Other
AGN	117 (21)	20	6	5	86
White Dwarfs	94 (5)	2	86	35	3
Emission Stars	44 (22)	3	12	20	15
CV (AM-Her)	19 (0)	3	16	0	3
CV (DQ-Her)	2 (0)	1	1	1	0
CV (Nova Like)	1 (0)	1	0	1	0
CV (Unclassified)	1 (1)	0	0	0	1
CSPN	5 (0)	0	3	2	2
Symbiotic Stars	3 (0)	0	3	2	0
Pulsars	3 (0)	0	1	0	2
Novae	2 (0)	0	1	1	1
Nuclear Burning WD	2 (0)	0	1	1	1
Early Stars (O1-F5)	>36 (?)	0	6	22	5
Late Stars (F6-M9)	>89 (?)	0	15	57	23

An example of the type of spectra we are accumulating during this project is shown for SXS AGN in Figure 4. The spectra of four newly identified sources (at a variety of redshifts) are plotted in the figure. In addition to the obvious emission lines, iron emission complexes are noted on either side of the [OIII] doublet. These features are found in most of our SXS AGN and may be due to reprocessing by a warm absorber. However, note there is nothing obviously different on the optical spectra of SXS AGN compared to the diverse varieties (e.g. emission line ratios) in hard X-ray selected samples. The combination of optical and X-ray spectra will help us determine the physical mechanisms responsible for the 0.1-0.4 keV emission. A supporting SAX proposals has been submitted.

Finally, we note that we have yet to find a new NBWD; however, we will be looking in the southern hemisphere for the first time during spring, 1996. This, in combination with the new "Monte Carlo selected sample," improves our chances of finding new systems of this type.

5 Summary

The WGA and SRC catalogs provide a complementary data set to the RASS, trading sky coverage for a factor of ~20 in average exposure time. We are halfway through a two-year program to identify SXS in the pointed catalogs. At this point, we can confirm that the RASS results regarding AM Her CVs (this subclass dominates all SXS CVs) and AGN (there are more SXS AGN than previously thought) still hold in our work. Although no new NBWDs have been found, we have made steady progress identifying new optical counterparts to SXS, most of which are AGN and emission stars.

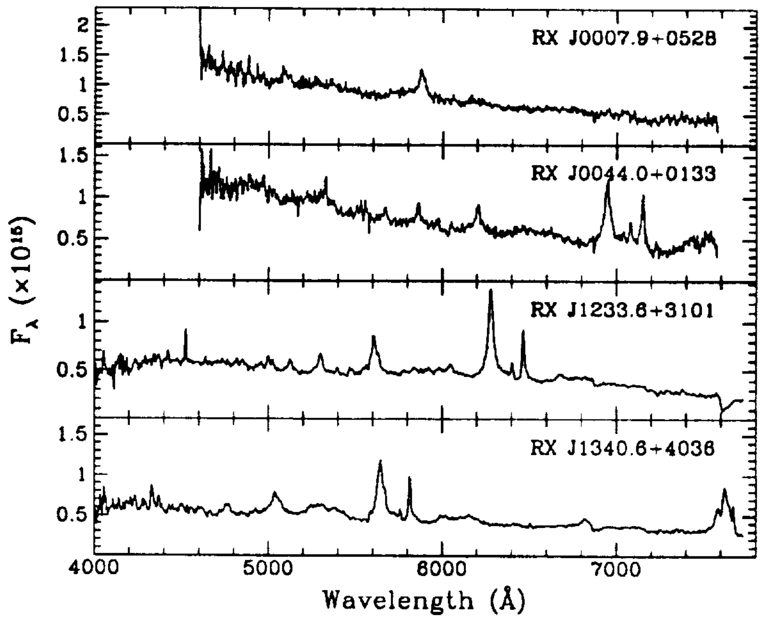

Fig. 3. Optical spectra of four newly identified SXS AGN. The redshifts (top to bottom) are 1.1, 0.44, 0.29, and 0.16.

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